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Research Article

Conservation priorities for threatened mammals of Vietnam: Implementation of the IUCN´s One Plan Approach

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Abstract

Vietnam belongs to one of the most well-known global biodiversity hotspots. However, its biodiversity is being threatened by multiple factors such as rapid growth of the human population, habitat destruction, overexploitation, and climate change. To better prioritize conservation measures for Vietnam's mammal fauna, this study attempts to identify the threat status, level of endemism, and protected area coverage for approximately 329 recognized taxa. In addition, *ex situ* conservation measures are investigated by analyzing zoo databases. Our results show that as many as 112 mammal species (~34%) in Vietnam are officially listed as threatened, 36 (~11%) are country endemics, and nine (~3%) are micro-endemic. Nearly all threatened species are currently covered by protected areas, except for two species of high conservation importance, i.e., the micro-endemic *Murina harpioloides* (Chiroptera) and the threatened *Lepus sinensis* (Lagomorpha). Our results also suggest that such areas as Hoang Lien Range, northeastern Vietnam, and the central and southern Annamite Mountains require more conservation attention, as they harbor a high number of endemic species. Analyses of the Zoological Information Management System reveal that roughly 60% (67 species) of threatened species are currently kept in zoos (*ex situ*) across the world, while none of the species listed as "Data Deficient" are currently represented in any *ex situ* program. Up to 66% of 89 species kept in zoos show a good number of breeding successes in the past 12 months. It is recommended that future conservation efforts focus on unprotected threatened mammals and on evaluating the threat status for "Data Deficient" species. Additionally, the existing protected area system's effectiveness should be improved by creating corridors to provide connectivity for highly mobile and widely distributed mammal species.

Key words: Conservation breeding, diversity analysis, endemic species, mammal conservation, protected area coverage, richness analysis, threat assessment

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Introduction

The consequences of anthropogenic climate change and destructive land use have led, and are leading, to the global biodiversity crisis (Habel et al. 2019; Ceballos et al. 2020). The International Union for Conservation of Nature and Natural Resources (hereafter IUCN) currently lists about 41,000 species as threatened with extinction. With regard to mammals, up to 27% are currently classified as threatened (IUCN Red List 2024).

Climate change is currently affecting 19% of species listed as threatened or near threatened by the IUCN (Maxwell et al. 2016). Besides climate change, the biggest threats to biodiversity today are overexploitation of wild animals and natural resources, as well as habitat loss due to intensification of agriculture (Maxwell et al. 2016). Wild animals are most threatened by the global unsustainable use of bush meat, while at the same time, many people around the world are dependent on this source of protein for nutrition (Mainka and Trivedi 2002). As the anthropogenic climate change is accelerating, a higher proportion of wild animals is expected to be threatened in the future (Habel et al. 2019). Hence, it is expected that greater numbers of species will require urgent conservation actions. Thus, the conservation goal today is not only to avoid extinction but also to focus on species recovery (Redford et al. 2011).

For enhancing conservation measures, the Conservation Planning Specialist Group (CPSG) of the IUCN Species Survival Commission (SSC) proposed the One Plan Approach to Conservation, which aims to combine conservation efforts, from both inside (*in situ*) and outside (*ex situ*) species natural ranges (Byers et al. 2013). On top of that, it outlines the objective to develop one integrated conservation plan for all threatened species (IUCN/SSC 2014).

In order to at least slow down or at best prevent further loss of biodiversity, species need to be safeguarded within protected areas (PAs), an effective measure to achieve long-term conservation of nature and healthy ecosystems (MacKinnon et al. 2020). As a complementary action to *in situ* conservation, whether because it is difficult or impossible to carry out at time, *ex situ* conservation has been demonstrated to be a crucial solution through building up assurance colonies of animals, viz. by keeping and breeding them in zoological institutions. In comparison to *in situ* conservation, the main difference is the ability to buy time (Byers et al. 2013). Successful breeding programs, which enable the restoration of wild populations at a later stage once problems on site are resolved, have saved many species from extinction (Price 1989; Goodwin and Langenhorst 2014; Larska and Krzysiak 2019). In addition to maintaining assurance colonies of threatened species, zoos also actively support *in situ* conservation measures with monitoring and restocking projects or expertise acquired through ex situ conservation programs (Che-Castaldo et al. 2018).

As one of the global biodiversity hotspots, Vietnam hosts a large variety of ecosystems, with high mountains reaching up to more than 3000 m above sea level and a 3260 km long coastline (Rambaldi et al. 2001) and inland lakes and rivers like the Red River and Mekong River with their significant deltas (Sterling et al. 2006). The country is home to more than 300 mammal species (Nguyen et al. 2020), with 20% categorized as globally threatened (IUCN 2024). Within Vietnam, there are a number of areas with exceptional species richness and often a high proportion of endemic species. One example for those endemism centers

is the Annamite Mountain Range stretching primarily along the Lao-Vietnamese border with massive mountain ridges (Sterling et al. 2006; Tilker et al. 2019; CEPF 2020). Vietnam's mammal species are currently threatened by habitat loss and degradation (McDonald et al. 2018), poaching (Mainka and Trivedi 2002), and a lack of knowledge on species distribution and threat status (Borgelt et al. 2022).

The aim of the present study is to assess priorities of *in situ* and *ex situ* conservation for threatened mammals of Vietnam. Specifically, we investigated: 1. How is the mammal fauna of Vietnam distributed when accounting for species specific habitat preferences and where are centers of local endemism that require special conservation attention? 2. Which species are not yet covered by protected areas? 3. Which proportion of the mammal fauna is sufficiently represented in zoological collections to serve as backup populations, and how do global zoological institutions invest in conserving Vietnam's mammal fauna? 4. Which actions are needed to improve both *in situ* and *ex situ* efforts?

Materials and methods

Species list

The initial species list was based on the "Checklist of Mammals in Vietnam" (Dang et al. 2008). Additional species were incorporated using more recent publications. While the majority of taxa were included in analyses based on the species level, six subspecies were incorporated in the study, because they are valid taxa and reported to occur in Vietnam (*Chodsigoa parca lowei*, *Callosciurus finlaysonii honnghensis*, *Mustela nivalis tonkinensis*, *Murina lorelieae ngoclinhensis*, *Panthera tigris corbetti*, and *Rhinolophus rex paradoxolophus*). *Euroscaptor parvidens ngoclinhensis* was elevated to species status, *Euroscaptor ngoclinhensis* (Bui et al. 2020), and *Muntiacus puhoatensis* was synonymized with *M. rooseveltorum* based on findings of recent molecular analysis (Le M, unpublished data).

Species distribution

Species distribution data was obtained from the IUCN Red List in August 2022. For species whose distributions were not clearly specified in the list (Table 1), shapefiles were generated using software package QGIS 3.24. Their distribution ranges were generated based on records extracted from various research papers as well as those available at the Institute of Ecology and Biological Resources (IEBR) in Hanoi (Nguyen ST, Motokawa M, and Oshida T, unpublished data). As range estimate, radial buffers of 20 km around each record were used. *Mus cervicolor* and *Olisthomys morrisi* were not included, because these species ranges are currently unknown.

Species range estimates were refined using relevant functions of the rredlist (Gearty et al. 2022) and raster package v3.6-26 (Hijmans et al. 2023) for R 4.2.2. by accounting for the availability of suitable microhabitats within the range polygons as mapped by Jung et al. (2020). The microhabitat map had a spatial resolution of 100 m and is based on habitat types as defined by the IUCN (Jung et al. 2020). Subsequently, we assessed for each protected area, in which species are likely to occur given its suitable habitats. Finally, we computed species richness maps and identified areas of high local endemism using

the corrected weighted endemism approach (Crisp et al. 2001). While species richness only measures the total count of species per grid cell, the weighted endemism approach specifically focuses on range-restricted species. The species distribution areas get scored by how many grid cells they obtain. The more grid cells they cover, the lower the score per species. The scores of all endemic species per cell are summed up to calculate the weighted endemism.

Distribution categories

For classifying species distribution, QGIS was used to construct a map of Vietnam´s biogeographic regions (see Fig. 1). The regions are based on those proposed by Bain and Hurley (2011) and the "Terrestrial Ecoregions of the World" (Olson et al. 2001). Two areas of endemism, Cat Ba Island and Hoang Lien Mountain Range, were added based on the number of endemic species reported from the area. The map's underlying shapefiles were drawn from the World Wildlife Fund's map (Olson et al. 2001).

Species distributions were categorized as summarized in Table 1.

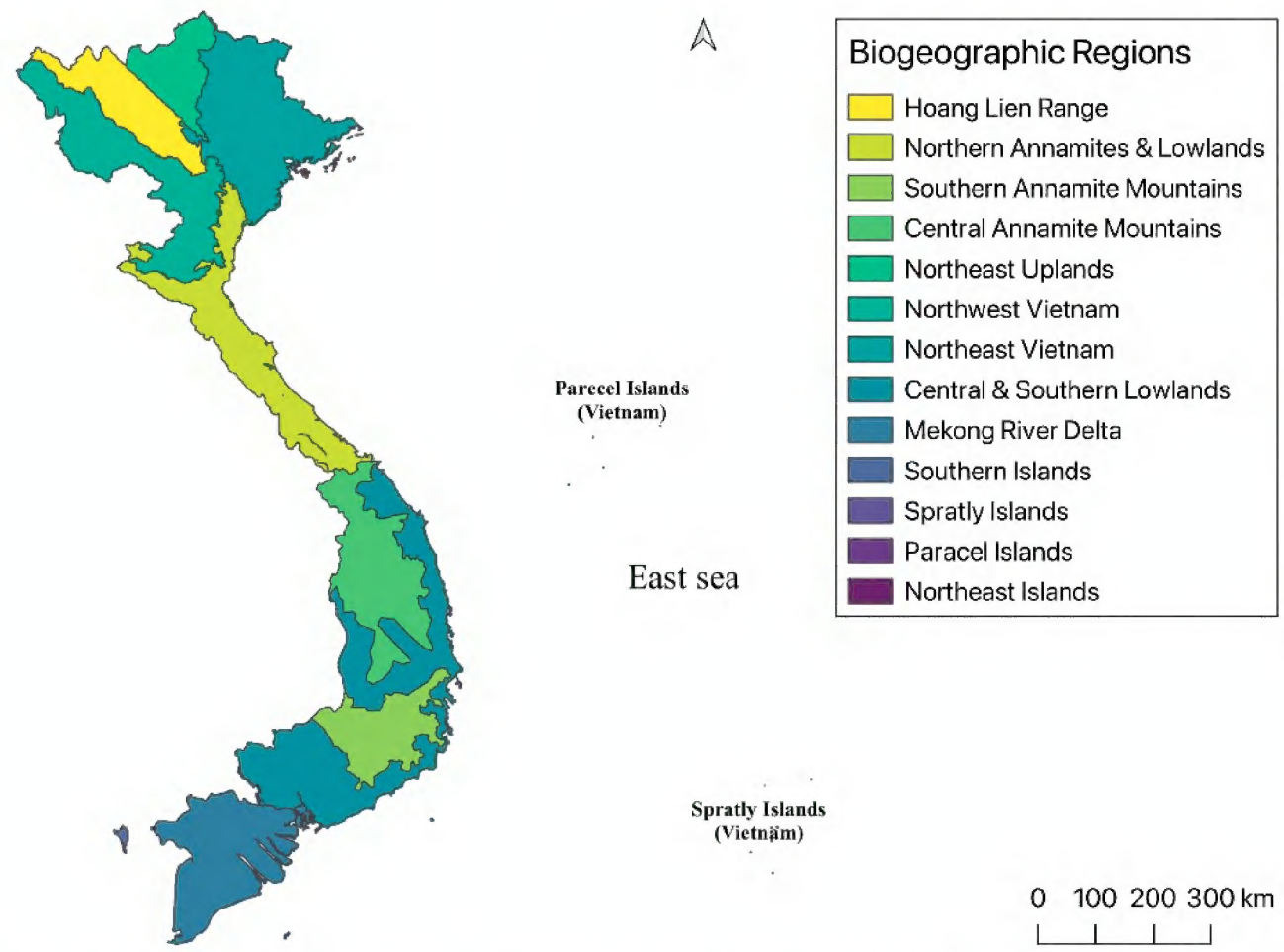

Figure 1. Biogeographic regions of Vietnam sorted from highest elevation values to lowest.

Table 1. Criteria for classifying distribution areas of mammals in Vietnam.

Distribution Category	Criteria
Endemic	Exclusively distributed within Vietnam borders
Widespread	Distributed over multiple biogeographic regions in Vietnam
Regionally Endemic	Exclusively distributed within Vietnam borders. Distributed in only/mostly one biogeographic region in Vietnam
Micro-Endemic	Exclusively distributed within Vietnam borders. Distributed in only one biogeographic region and the distribution area covering at most 1% of the total area of Vietnam (≤ 3,317 m^2)
Cross-Border Species	Not endemic to Vietnam but the distribution area within Vietnam covering at most 1% of the total area of Vietnam

Some species were categorized as regionally endemic and widespread. The former applies to species which are distributed in two bordering biogeographic regions, but at least 80% of the distribution is in one of the regions.

Threat status assessment

For assessment of the individual threat status of each species, four different data sources were used: the IUCN Red List (IUCN 2024; version 2024.1), the Vietnam Red Data Book (VNRDB 2024) (in press), appendices of the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES), and the updated Decree on management of endangered, precious and rare forest plants and animals and implementation of the Convention on International Trade in Endangered Species of Wild Fauna and Flora (hereafter Decree 84/2021). Where data sources showed distinct discrepancies in ranking a species, the most recent assessment was used. Decree 84/2021 includes threatened species of wild fauna and flora of Vietnam. It was developed according to the Vietnamese law on biodiversity enacted in 2017 (Law No. 16/2017/QH14 on Forest Law 2017) and serves as a legal document for species protection, focusing on endangered and heavily traded taxa.

Species are considered threatened if they are either classified as VU, EN or CR by the IUCN Red List and/or by the VNRDB or listed in appendices CITES as of 2022 and/or in Decree 84/2021. Species which are referred to as "Data Deficient" (DD) are those not listed in any of the databases used for assessing threat status or listed as DD in the existing databases.

In situ populations / Protected area and OECM coverage

The World Database of Protected Areas (WDPA) and the World Database of Other Effective Area-Based Conservation Measures (WDOECM) are the most comprehensive databases on terrestrial and marine PAs and OECMs. For Vietnam, there are no OECMs listed in the database. Protected Areas in Vietnam are designated in eleven different categories. All designations are followed when referring to PAs.

Ex situ populations / Husbandry database

The Species 360 Zoological Information Management System (ZIMS) (Species360 2022) was used to analyze the representation of Vietnamese mammals in zoos worldwide. The ZIMS data was downloaded on August 19th and 20th 2022. All institutions listed in ZIMS are in the following referred to as zoos. Although this is the most comprehensive database for animal holdings, it is important to note that not all zoological institutions worldwide contribute their data to ZIMS.

Information of species categorized as threatened in Vietnam currently kept in zoos worldwide was included in our analysis. Of particular interest was the number of threatened, micro-endemic and DD species and their breeding success in the past 12 months. To create an overview of Vietnamese mammals in zoo holdings worldwide, a map was generated. It contains the number of zoos per country which are keeping mammals documented in Vietnam and the number of individuals per zoo. The mammal species diversity of each institution was illus-

trated using the Shannon-Weaver Index ($H = - \Sigma p_i log(b) p_i$) (Shannon and Weaver 1994) computed with the R package vegan v2.6-4 (Oksanen et al. 2022), where p_i is the proportion of species i, and the sum is over the total number of species.

Results

Mammal diversity

The total number of mammal taxa in Vietnam was estimated at 329, including the six subspecies *Chodsigoa parca lowei*, *Callosciurus finlaysonii honnghensis*, *Mustela nivalis tonkinensis*, *Murina lorelieae ngoclinhensis*, *Panthera tigris corbetti*, and *Rhinolophus rex paradoxolophus*. A list of species with endemism levels is presented in Suppl. material 1. With 128 species, Chiroptera is the most speciose order and makes up around 39%, followed by Rodentia with 77 species, accounting for 23.4% of the total mammal diversity in Vietnam. Five orders, only represented by very few species, include Lagomorpha with three, Pholidota and Scandentia both with two, and Dermoptera and Proboscidea with only one species each. Among 36 families of mammals recorded in Vietnam, the ten most diverse families belong to six orders with greatest species richness, i.e., Chiroptera, Rodentia, Carnivora, Eulipotyphla, Primates, and Artiodactyla (Suppl. material 1).

Species distribution and richness analysis

Vietnam is home to 36 endemic mammals, making up approximately 11% of the country's mammal diversity. The distribution analysis revealed a total of nine micro-endemic species listed in Table 2, *Tragulus versicolor* (Artiodactyla), *Trachypithecus poliocephalus* (Primates) and *Murina kontumensis* (Chiroptera) are also listed as threatened. Another five micro-endemic species are classified as DD.

Table 2. Micro-endemic mammal species in Vietnam (distribution area is 1% of the total area of Vietnam at most).

Order	Family/Subfamily	Scientific Name	Distribution
ARTIODACTYLA	**Tragulidae**	*Tragulus versicolor*	Southern Annamite Mountains (Ninh Thuan, Khanh Hoa)
CHIROPTERA	**Vespertilionidae**		
	Murininae	*Murina harpioloides*	Central Highland Mountains (Lam Dong)
EULIPOTYPHLA	**Soricidae**		
	Crocidurinae	*Crocidura annamitensis*	Northern Annamite Mountains (Huong Son Camp, Ha Tinh)
		C. guy	Northeast Vietnam (Tuyen Quang)
		C. phuquocensis	Southern Island (Phu Quoc)
		C. sokolovi	Central Annamite Mountains (Ngọc Linh, Kon Tum)
PRIMATES	**Cercopithecidae**		
	Colobinae	*Trachypithecus poliocephalus*	Northeast Vietnam Islands (Cat Ba)
RODENTIA	**Sciuridae**		
	Callosciurinae	*Callosciurus honkhoaiensis*	Mekong River Delta (southern island, Hon Khoai Island)
	Muridae		
	Murinae	*Rattus germaini*	Southern Island (Con Son Island)

Table 3. Important cross-border species with threat status assessment.

Order	Family/Subfamily	Scientific Name	Threat Status (IUCN 2024/VNRDB 2024)
CHIROPTERA	**Emballonuridae**	*Saccolaimus saccolaimus*	LC (IUCN)
	Hipposideridae	*Hipposideros khaokhouayensis*	VU (IUCN) EN (VNRDB)
	Pteropodidae	*Pteropus hypomelanus*	NT (IUCN) EN (VNRDB)
	Rhinolophidae	*Rhinolophus osgoodi*	LC (IUCN)
	Vespertilionidae		
	Myotinae	*Myotis annamiticus*	DD (IUCN)
	Murinae	*Murina chrysochaetes*	DD (IUCN)
EULIPOTYPHLA	**Soricidae**		
	Crocidurinae	*Crocidura wuchihensis*	DD (IUCN)
RODENTIA	**Muridae**		
	Murinae	*Saxatilomys paulinae*	DD (IUCN) VU (VNRDB)
		Tonkinomys daovantieni	DD (IUCN) VU (VNRDB)

According to the analysis, some species were revealed not to be endemic to Vietnam, but their distribution range within the country corresponded at most 1% of the landmass. Those nine species classified as important cross-border species are listed in Table 3. *Crocidura wuchihensis* (Eulipotyphla), *Murina chrysochaetes*, and *Myotis annamiticus* (Chiroptera) are important cross-border species which are listed as DD. Four other species are important cross-border species and are also threatened, comprising *Hipposideros khaokhouayensis* (Chiroptera), *Pteropus hypomelanus* (Chiroptera), *Saxatilomys paulinae* (Rodentia), and *Tonkinomys daovantieni* (Rodentia).

The species richness analysis suggested that the richness hotspots are located mostly in montane areas (Fig. 2). “Northwest Vietnam”, “Hoang Lien Range”, “Northeast Uplands”, “Northeast Vietnam” and the “Annamite Mountains” harbored a high level of mammal richness with a great proportion of threatened species.

The southern part of “Northwest Vietnam”, the “Northern Annamites” and the northern part of the “Central Annamite Mountains” showed an exceptional richness density. Analyses of micro-endemic and cross-border species richness confirmed their high concentration on island habitats like Cat Ba in the Northeast or Con Dao and Phu Quoc in the South. The larger area that stands out on the micro-endemic species map belongs to the distribution range of *Tragulus versicolor* (Artiodactyla). The cross-border species marked with a red area in the “Northwest Vietnam” region is *Rhinolophus osgoodi* (Chiroptera) (Fig. 2). The weighted endemism analysis revealed a slightly different picture in emphasizing the importance of northern Vietnam, central and southern Annamite Mountains, and offshore islands.

Threat assessment

In total, 112 species are currently categorized as threatened. This makes up around 34% of all mammal species in Vietnam and leaves 217 species without threat status (see Suppl. material 1). Out of the 11 orders of mammal species in Vietnam, nine include threatened species (Fig. 3). Scandentia contains no threatened taxa. Dermoptera and Proboscidea are each only represented by one species in Vietnam, and both are regarded as threatened (*Galeopterus variegatus*,

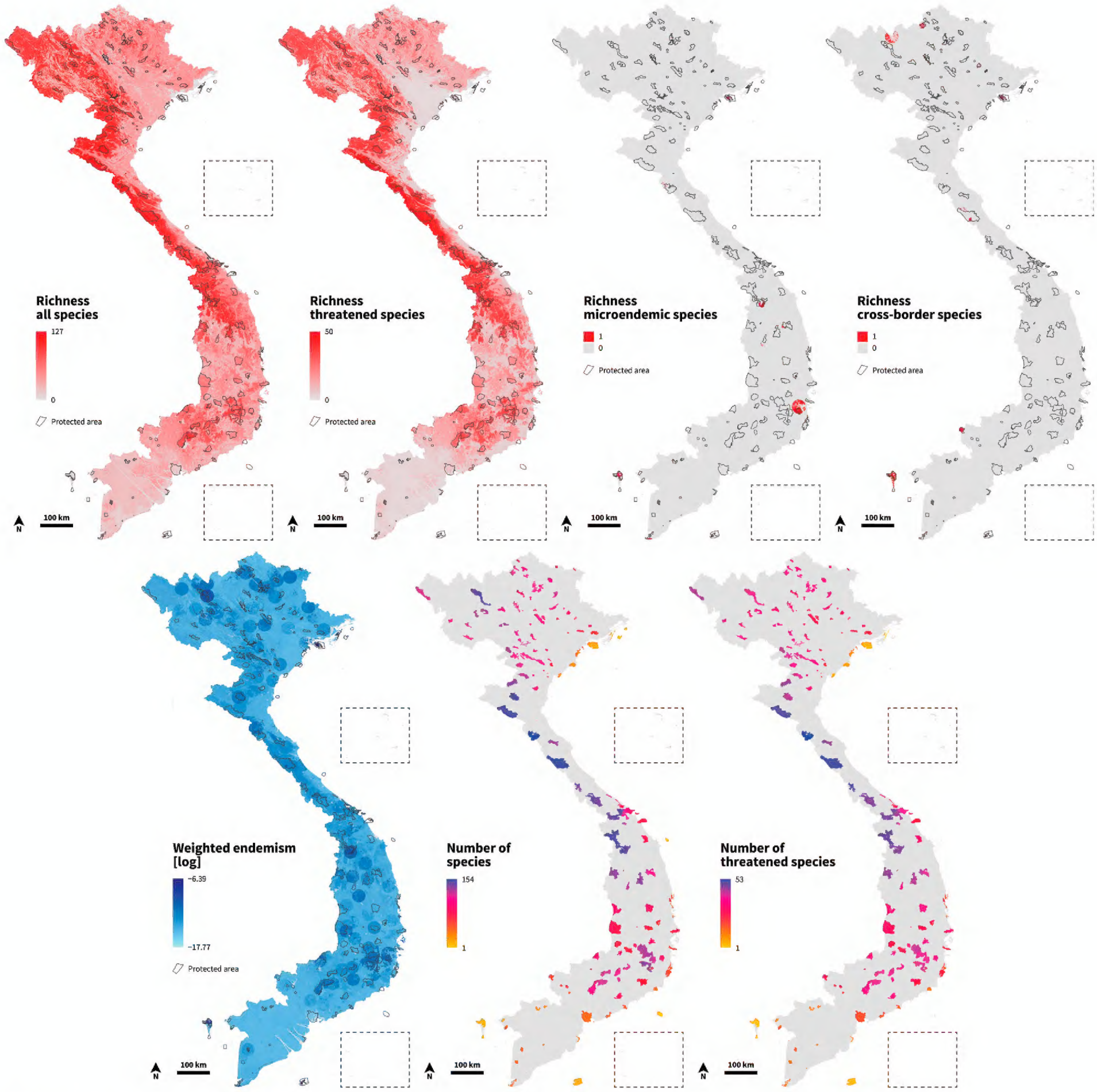

Figure 2. Richness analysis, weighted endemism, and protected area coverage.

Figure 3. Number and percentage of threatened mammal species in Vietnam per order.

Elephas maximus). The Pholidota and Lagomorpha both consist of two threatened species each, namely *Manis javanica* and *M. pentadactyla*, *Nesolagus timminsi* and *Lepus sinensis*, respectively.

Carnivora, Primates, Chiroptera, Artiodactyla and Rodentia are the five orders with the highest numbers of threatened species, three of which comprise more threatened than non-threatened species. Specifically, approximately 78% of Carnivores and 88% of Artiodactyla in Vietnam are considered threatened but even more concerning is 100% of Primates assessed as the same status. While 95% of the 112 threatened species are listed in the IUCN Red List and 96% in the VNRDB, only 17% are listed in CITES and 68% in Decree 84/2021. One species listed as micro-endemic was also categorized as threatened, and therefore incorporated with both groups. This concerns the Cat Ba Langur (*Trachypithecus poliocephalus*) (Cercopithecidae, Primates). In Vietnam 61 species are categorized as "Data Deficient" (DD) (see Table 4). The important cross-border species *Crocidura wuchihensis* and *Murina chrysochaetes* are also classified as DD. Five of nine (56%) micro-endemic taxa fall into this category. In the following, these species were included in both datasets, i.e., DD and micro-endemic.

Most DD species belong to the order Eulipotyphla (21 species), followed by Chiroptera (20 species) and Rodentia (16 species). Those species are all quite small and elusive, making them difficult to study in the field.

Table 4. Data deficient (DD) species or subspecies, not listed in any of the databases used for the threat status assessment or classified as DD.

Order	Family / Subfamily	Scientific Name
CARNIVORA	**Herpestidae**	*Urva javanica*
		U. urva
	Mustelidae	
	Mustelinae	*Melogale cucphuongensis*
		Mustela nivalis tonkinensis
CHIROPTERA	**Emballonuridae**	*Taphozous longimamus*
	Miniopteridae	*Miniopterus fuliginosus*
	Rhinolophidae	*Rhinolophus chaseni*
		R. perniger
		R. yunnanensis
	Vespertilionidae	
	Murininae	*Murina chrysochaetes*
		M. walstoni
	Myotinae	*Myotis alticraniatus*
		M. ancricola
		M. annamiticus
		M. annatessae
		M. indochinensis
		M. montivagus
		M. phanluongi
	Vespertilioninae	*Cassistrellus yokdonensis*
		Hypsugo dolichodon
		Mirostrellus joffrei
		Tylonycteris fulvida
		T. malayana
		T. tonkinensis

Order	Family / Subfamily	Scientific Name
EULIPOTYPHLA	**Soricidae**	
	Crocidurinae	*Crocidura annamitensis*
		C. dracula
		C. guy
		C. kegoensis
		C. phuquocensis
		C. rapax
		C. sapaensis
		C. sokolovi
		C. wuchihensis
	Soricinae	*Chimarrogale varennei*
		Chodsigoa caovansunga
		C. hoffmanni
		Episoriculus baileyi
		E. umbrinus
	Talpidae	
	Talpinae	*Euroscaptor kuznetsovi*
		E. orlovi
		E. ngoclinensis
		E. parvidens
		E. subanura
		Mogera latouchei
		Uropsilus fansipanensis
RODENTIA	**Muridae**	
	Murinae	*Berylmys mackenziei*
		Chiromyscus langbianis
		C. thomasi
		Dacnomys millardi
		Hapalomys suntsovi
		Leopoldamys herberti
		L. revertens
		Micromys erythrotis
		Niviventer bukit
		N. lotipes
		N. mekongis
		Rattus germaini
	Sciuridae	
	Callosciurinae	*Callosciurus finlaysonii honnghensis*
		Dremomys gularis
		Tamiops macclellandii
	Sciurinae	*Olisthomys morrisi*

In situ populations / Protected area coverage

In our analyses, 175 PAs were reviewed. Fig. 2 shows the number of species covered by each PA. During analysis of the species' PA coverage, the focus was placed on threatened and micro-endemic species. Approximately 83% of those are already protected by at least three PAs in Vietnam with eight more species currently distributed within at least two protected areas. Four of those eight are micro-endemic and five are threatened species. One micro-endemic species is listed as threatened, while the other three micro-endemic species are DD. Table 5 lists all threatened and micro-endemic species, which occur in only one or zero PAs in Vietnam. Of a total of ten species, seven are threatened. Species currently not covered by any PA include micro-endemic *Murina harpioloides* (Chiroptera) and threatened *Lepus sinensis* (Lagomorpha).

Ex situ records/Husbandry database

A total of 89 mammal species reported from Vietnam (27% of all species) are currently kept in zoos and about 75% (67 species) of those are classified as threatened. This makes up roughly 60% of all threatened species, leaving as many as 45 threatened species unprotected by *ex-situ* measures (Table 6). They consist of three important cross-border species, i.e., *Hipposideros khaokhouayensis* (Chiroptera), *Saxatilomys paulinae* and *Tonkinomys daovantieni* (Rodentia) as well as two micro-endemic species, namely *Callosciurus honkhoaiensis* (Rodentia) and *Tragulus versicolor* (Artiodactyla), which is also listed as threatened. None of the species listed as DD are currently kept in zoos.

The Cat Ba Langur (*Trachypithecus poliocephalus*) is the only micro-endemic species currently kept in a zoological facility, the Endangered Primate Rescue Center in Cuc Phuong National Park, northern Vietnam. Of all threatened species, around 48% are kept in two institutions or fewer.

Fig. 4 presents the husbandry data of the threatened mammals included in this study. It shows the number of zoos per country, as well as specific numbers of held individuals. There is a high abundance of zoos keeping threatened mammals in the USA, Europe, the United Kingdom, and Japan. However, those in India and Southeast Asian have much greater diversity index and number of held individuals.

Regarding the number of species held in zoos, there are a few only represented by a single individual, including four following threatened species: *Pygathrix nigripes*, *Hylopetes alboniger*, *Petaurista elegans*, and *Prionodon pardicolor*. A total of 56 species, roughly 88% of threatened taxa, are kept in same-sex populations in at least one institution. Assessing the breeding success of threatened species in zoos has shown that most threatened species (66%) are being successfully bred under human care. For 22 species (34%), breeding has remained unsuccessful in the past 12 months (before August 2022) including the ones held in same-sex groups.

Table 5. Threatened and micro-endemic mammal species in Vietnam, which occur in one or zero PA and their threat status assessment.

Order	Family/ Subfamily	Scientific Name	Distribution Category	Threat Status (IUCN 2024/VNRDB 2024)
CHIROPTERA	**Vespertilionidae**			
	Murininae	*Murina harpioloides*	micro-endemic	EN (VNRDB) EN (IUCN)
	Myotinae	*Myotis formosus*	widespread	NT (IUCN)
EULIPOTYPHLA	**Soricidae**			
	Crocidurinae	*Crocidura annamitensis*	micro-endemic	DD (IUCN)
		C. guy	micro-endemic	DD (IUCN)
LAGOMORPHA	**Leporidae**	*Lepus sinensis*	widespread	EN (VNRDB)
RODENTIA	**Diatomyidae**	*Laonastes aenigmamus*	widespread	VU (VNRDB)
	Muridae			
	Murinae	*Saxatilomys paulinae*	Important Cross-Border Species	VU (VNRDB)
		Tonkinomys daovantieni	Important Cross-Border Species	VU (VNRDB)
	Sciuridae			
	Callosciurinae	*Callosciurus honkhoaiensis*	micro-endemic	

Table 6. Threatened mammal species or subspecies, which are currently not kept in zoos.

Order	Family / Subfamily	Scientific Name	Endemic
ARTIODACTYLA	**Bovidae**		
	Bovinae	*Pseudoryx nghetinhensis*	*N*
	Cervidae		
	Cervinae	*Muntiacus truongsonensis*	*N*
		M. vuquangensis	*N*
		M. rooseveltorum	*N*
	Moschidae	*Moschus berezovskii*	*N*
	Tragulidae	*Tragulus versicolor*	*Y*
CARNIVORA	**Mustelidae**		
	Lutrinae	*Lutra sumatrana*	*N*
	Mustelinae	*Mustela strigidorsa*	*N*
CHIROPTERA	**Hipposideridae**	*Coelops frithii*	*N*
		Hipposideros alongensis	*Y*
		H. griffini	*Y*
		H. khaokhouayensis	*N*
		H. lylei	*N*
		H. scutinares	*N*
		H. swinhoei	*N*
	Molossidae	*Mops plicatus*	*N*
	Pteropodidae		
		Macroglobosus minimus	*N*
	Rhinolophidae	*Rhinolophus episcopus*	*N*
		R. marshalli	*N*
		R. rex paradoxolophus	*N*
	Vespertilionidae		
	Kerivoulinae	*Kerivoula picta*	*N*
	Murininae	*Harpiola isodon*	*N*
		Murina harpioloides	*Y*
		M. kontumensis	*Y*
		M. lorelieae ngoclinhensis	*N*
		Phoniscus jagorii	*N*
	Myotinae	*Myotis formosus*	*N*
		M. pilosus	*N*
	Vespertilioninae	*Barbastella darjelingensis*	*N*
		Ia io	*N*
		Scotomanes ornatus	*N*
		Thainycteris aureocollaris	*N*
LAGOMORPHA	**Leporidae**	*Lepus sinensis*	*N*
		Nesolagus timminsi	*N*
PRIMATES	**Cercopithecidae**		
	Colobinae	*Rhinopithecus avunculus*	*Y*
		Trachypithecus crepusculus	*N*
		T. francoisi	*N*
	Hylobatidae	*Nomascus nasutus*	*N*
RODENTIA	**Diatomyidae**	*Laonastes aenigmamus*	*N*
	Muridae		
	Murinae	*Saxatilomys paulinae*	*N*
		Tonkinomys daovantieni	*N*
	Platacanthomyidae	*Typhlomys chapaensis*	*N*
	Sciuridae		
	Sciurinae	*Belomys pearsonii*	*N*
		Hylopetes phayrei	*Y*
		Petaurista philippensis	*N*

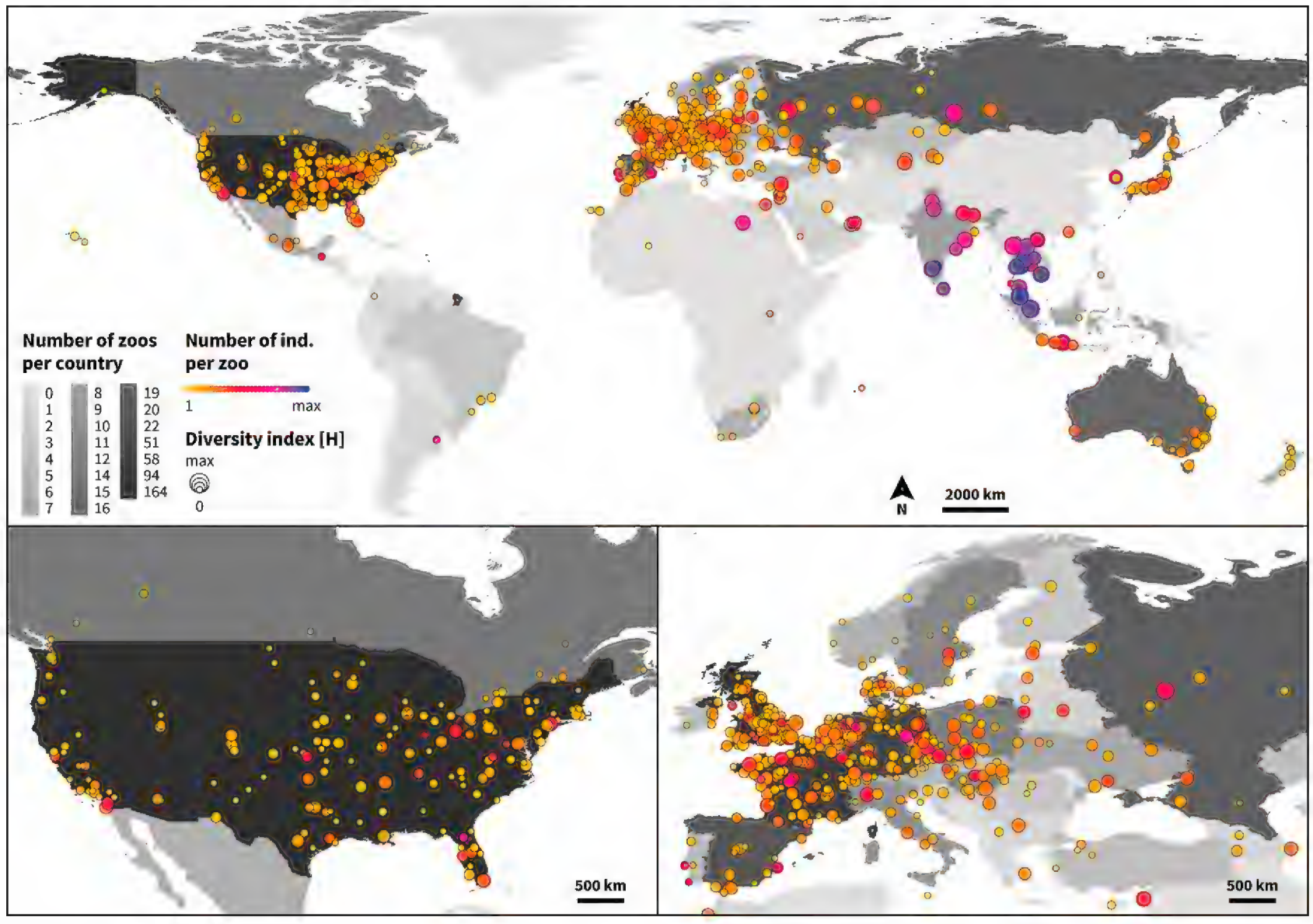

Figure 4. Ex situ preservation of threatened Vietnamese mammals worldwide.

Discussion

Assessment of conservation priorities

This study shows that up to 34% of the 329 mammals in Vietnam are currently listed as threatened. The weighted endemism analysis highlights mammal diversity hotspots in montane areas, such as central and southern Annamites. These areas of endemism were also previously highlighted for conservation prioritization in a study on Vietnamese amphibians (Krzikowski et al. 2022). The distribution range of the micro-endemic species *Murina harpioloides* (Chiroptera) also falls within central Annamite Mountains. Micro-endemic species will especially benefit from urgent conservation measures, as they will be particularly vulnerable to extinction risks due to their restricted range. *In-situ* conservation measures are apparently needed for the threatened *Lepus sinensis* (Lagomorpha), as it is currently not protected in its natural habitat. Additionally, five other threatened species (*Myotis formosus*, *Laonastes aenigmamus*, *Saxatilomys paulinae*, *Tonkinomys daovantieni* and *Callosciurus honkhoaiensis*) are currently covered by only one PA. This raises concern because they are not sufficiently safeguarded and therefore, other distribution areas of the species should also be a focus when it comes to designating new PAs.

Regarding *ex situ* conservation measures, a total of 45 threatened species from Vietnam are not currently represented in any zoos (Table 6). Several others are present in only one or two institutions. Nonetheless, keeping species in a network of facilities is important for stable, resilient backup populations in case a zoo population is lost unexpectedly, e.g., by a disease outbreak (Ziegler et al. 2020). In addition, well-organized studbooks help to protect the gene pool from depletion (Glatston 2001). Assurance populations in the country of origin

are optimal in terms of reduced bureaucracy and high feasibility of restocking, whereas facilities in other range states are helpful in case of disease outbreaks, natural catastrophes, or political unrest at the sites. In any case, the buildup of assurance colonies and a conservation breeding network help to buy time in case *in situ* conservation measures cannot be implemented quickly enough and prevent any impending extinction crises from happening (Byers et al. 2013).

The Cat Ba Langur (*Trachypithecus poliocephalus*) (Primates) is the only micro-endemic species currently listed in ZIMS. It is held in a primate rescue center (the Endangered Primate Rescue Center – EPRC, Cuc Phuong National Park) in Vietnam with a breeding success listed in the last 12 months. Another eight micro-endemic species are not represented in any holdings around the world. It is also important to underline the 61 species listed as DD (Table 4). More than half of them are predicted to be threatened, emphasizing the priority for assessing their conservation status in the future (Borgelt et al. 2022). Although they account for 18.3% of all mammal species in Vietnam, none of them are currently kept in zoos.

The fact that 5 of 9 micro-endemic species are DD and lack information on their threat status is particularly concerning. Species with such small distributions have a much higher risk of being extirpated (McDonald et al. 2018) and critically need immediate conservation actions. This is also the reason why important cross-border species are included in this study. While the species are on top of the list for conservation priorities in Vietnam, they might not be protected in the neighboring countries either. Evaluating the importance of conserving these species in Vietnam requires further studies covering, amongst other things, their conservation status in other countries. In addition, for the species, transboundary conservation measures should be seriously considered in developing priority actions to secure their natural populations.

Data limitation

Assessments by the IUCN are not always up to date, as discernible from Suppl. Material 2 when the dates of the last assessments are noted. Numerous sources of error exist regarding ranges and distribution areas. This study presents an effort in reducing those by means of habitat analysis based on the shapefiles from IUCN and the newly generated ones. Despite that, distribution areas' accuracy varies widely, reflecting the details in data collected and research conducted until now (Ariño and Otegui 2015). For example, distribution areas of taxa like Eulipotyphla and Rodentia are often inaccurate (Kennerley et al. 2021). This is also a potential source of error in the species ranges areas created as part of this study. Due to a lack of information on the actual size of the distribution areas it was not possible to adjust the buffer zones for each species. We, however, used all records available for each species to estimate the distribution range in Vietnam as accurately as possible.

Furthermore, species ranges under a changing climate are shifting more rapidly than ever. This implies that accurate representations of species distributions today may change quickly in the next decades (Blair et al. 2022; Nguyen et al. 2022; Trinh-Dinh et al. 2022). This underscores the importance of updating information when it comes to conservation needs assessment. Achieving the goal to protect all threatened species of the world demands large scale exchange of information, topical analyses, and overcoming cross-border communication gaps (Bain and Hurley 2011).

Another potential source of error regarding species distribution is posed by ever-changing taxonomic knowledge, such as increasing recognition of cryptic taxa, viz. taxa previously being hidden under a name but in fact representing a species complex. Many recent studies are addressing cryptic diversity with integrative taxonomic approaches, combining morphological, ecological, and genetic evidence to discover new species. Such an example is Chiroptera, which potentially harbors a high level of cryptic diversity (Francis et al. 2010; Srinivasulu et al. 2019). In this study, we only include species recognized until the end of 2022, but since then several new taxa have been discovered (e.g., Blair et al. 2023; Bui et al. 2023).

Regarding the ZIMS database, there is the possibility of missing animal husbandry institutions because not all zoos contribute their data to ZIMS. Also, not all taxa reported to occur in Vietnam and kept in zoos derive from founders from Vietnam, and not all founders of ex situ populations were genetically screened for purity and/or geographic provenance. In addition, there are instances where a colony of species is currently kept in zoos, but the wild population no longer exists in Vietnam and future release of kept individuals is uncertain, e.g., *Cervus nippon pseudaxis*. We did not include such species in our analyses until the situation becomes clearer.

Outlook

Designating new PAs and increasing the representations of threatened and micro-endemic species held in zoos will constitute important and much needed conservation measures in a first instance, but in the long term this approach alone might not be enough to achieve successful outcomes. For *in situ* conservation it will thus be important to improve management effectiveness of existing PAs and continuously measure the management effectiveness rather than quantity of PAs (Geldmann et al. 2019). For this, other local socio-economic issues, like poverty and the dependency on natural resources such as bush meat, must be addressed through livelihood improvement programs (Mainka and Trivedi 2002). Besides that, political corruption has been shown to be closely correlated with poor conservation outcomes, as it reduces the effectiveness of conservation investments and overlooks illegal overexploitation (Bradshaw et al. 2009). Recent evidence shows that in most cases well-managed, well-connected protected areas have more likely achieved their conservation objectives (MacKinnon et al. 2020).

These problems cannot be resolved only by designating new protected areas, but by involving local people, resource extraction companies, governments and scientists in conservation actions (Milner-Gulland et al. 2003). Future tools for conservation planning should also integrate models of urban growth (McDonald et al. 2018), as growing human populations are increasingly in conflict with designating new PAs. *In situ* conservation could further be improved by establishing wildlife corridors between PAs. This measure does not apply to conservation of micro-endemic species, as their distribution areas are very small. However, it will certainly benefit a suite of other species, especially mobile and wide-ranging mammals and in the context of the global climate change where species shift their ranges in an unprecedented rate (Thapa et al. 2017). As Northern Annamites and Lowlands harbor concentrated species richness and some of the biggest PAs in Vietnam, creating corridors to connect the PAs could substantially aid the species conservation in the region. However, it

should also be considered that with changing habitats, it might be necessary to adjust prioritization for conservation towards species with a low chance of maintaining their natural habitat in the future. Taking this into account, further research is necessary combining ecosystem modifications due to climate change and species-specific habitat requirements.

Keeping and breeding Vietnam's threatened, micro-endemic and vastly overlooked taxa will be crucial for subsequent restoration of diminished or even extinct natural populations. The rewilding approach needs coordinated conservation breeding networks in zoos and stations both inside the country of origin and also outside as assurance colonies follow the modern ark principle. This is especially true for an effective implementation of the One Plan Approach, where the concepts of *ex situ* and *in situ* conservation support each other. In the case of Vietnam, the One Plan Approach is more important than ever because many Critically Endangered species either are extirpated/extinct or their populations are so severely depleted that it is difficult for them to recover without our timely interventions.

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Additional information

Conflict of interest

The authors have declared that no competing interests exist.

Ethical statement

No ethical statement was reported.

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Author contributions

TZ, MDL, STN conceptualized the study; HH, STN, PHD, MM, TO, DR, HTB, TQN, MDL, HTB, TZ led the data analysis and data curation; HH, TZ, MDL, DR led the writing and all authors edited and approved the manuscript.

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Data availability

All of the data that support the findings of this study are available in the main text or Supplementary Information.

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Supplementary material 1

List of all mammal species of Vietnam and their endemism analysis

Authors: Hanna Höffner, Son Truong Nguyen, Phuong Huy Dang, Masaharu Motokawa, Tatsuo Oshida, Dennis Rödder, Truong Quang Nguyen, Minh Duc Le, Hai Tuan Bui, Thomas Ziegler

Data type: docx

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Supplementary material 2

List of all threatened mammal species of Vietnam and their detailed threat assessment

Authors: Hanna Höffner, Son Truong Nguyen, Phuong Huy Dang, Masaharu Motokawa, Tatsuo Oshida, Dennis Rödder, Truong Quang Nguyen, Minh Duc Le, Hai Tuan Bui, Thomas Ziegler

Data type: docx

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